

The MSSM Higgs Sector at the LHC and Beyond

S. Heinemeyer

Instituto de Física de Cantabria (CSIC), E-39005 Santander, Spain

Some possibilities to test the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) at the LHC and future e^+e^- colliders are discussed. This includes precision coupling strength measurements, the search for additional Higgs bosons as well as their decay to supersymmetric particles.

I. INTRODUCTION

The ATLAS and CMS experiments at CERN have discovered a new boson with a mass around 125 GeV [1, 2]. Within the present experimental uncertainties this new boson behaves like the Higgs boson of the Standard Model (SM) [3]. However, the newly discovered particle can also be interpreted as the Higgs boson of extended models, where the Minimal Supersymmetric Standard Model (MSSM) [4] is a prime candidate. The Higgs sector of the MSSM with two scalar doublets accommodates five physical Higgs bosons. In lowest order these are the light and heavy \mathcal{CP} -even h and H , the \mathcal{CP} -odd A , and the charged Higgs bosons H^\pm . It can be expressed (at lowest order) in terms of the gauge couplings, the mass of the \mathcal{CP} -odd Higgs boson, M_A , and $\tan\beta \equiv v_2/v_1$, the ratio of the two vacuum expectation values. All other masses and mixing angles can therefore be predicted. Higher-order contributions can give large corrections to the tree-level relations [5, 6]. An upper bound for the mass of the lightest MSSM Higgs boson of $M_h \lesssim 135$ GeV had been obtained [7], in perfect agreement with the observed value of

$$M_H^{\text{exp}} = 125.09 \pm 0.24 \text{ GeV} , \quad (1)$$

as evaluated by the combination of ATLAS and CMS measurements [8].

We will review a few ways to test the MSSM Higgs sector at the LHC and beyond. We first briefly discuss the precision prediction for the lightest \mathcal{CP} -even Higgs boson mass in the MSSM. We review the status and the prospects of the Higgs coupling strength analyses at the LHC and the ILC. Finally we discuss where additional MSSM Higgs bosons could be discovered and review some precision calculations for their (potential) decay to supersymmetric (SUSY) particles.

II. THE LIGHTEST HIGGS BOSON MASS AS A PRECISION OBSERVABLE

In the MSSM the mass of the light \mathcal{CP} -even Higgs boson, M_h , can directly be predicted from the other parameters of the model. The accuracy of this prediction should at least match the one of the experimental result. The measured Higgs-boson mass value, Eq. (1), has already reached the level of a precision observable with an experimental accuracy of about 250 MeV. Consequently, it plays an important role in the context of testing the MSSM Higgs sector.

The status of higher-order corrections to M_h is quite advanced, see Refs. [9, 10] for the calculations of the full one-loop level. At the two-loop level [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26] in particular the $\mathcal{O}(\alpha_t\alpha_s)$ and $\mathcal{O}(\alpha_t^2)$ contributions ($\alpha_t \equiv h_t^2/(4\pi)$, h_t being the top-quark Yukawa coupling) to the self-energies – evaluated in the Feynman-diagrammatic (FD) as well as in the effective potential (EP) method – as well as the $\mathcal{O}(\alpha_b\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_b)$ and $\mathcal{O}(\alpha_b^2)$ contributions – evaluated in the EP approach – are known for vanishing external momenta. An evaluation of the momentum dependence at the two-loop level in a pure $\overline{\text{DR}}$ calculation was presented in Ref. [27]. A (nearly) full two-loop EP calculation, including even the leading three-loop corrections, has also been published [28]. However, the calculation presented in Ref. [28] is not publicly available as a computer code for Higgs-mass calculations. Subsequently, another leading three-loop calculation of $\mathcal{O}(\alpha_t\alpha_s^2)$, depending on the various SUSY mass hierarchies, has been performed [29], resulting in the code **H3m** which adds the three-loop corrections to the **FeynHiggs** [7, 12, 30, 31, 32] result. Recently, a combination of the full one-loop result, supplemented with leading and subleading two-loop corrections evaluated in the Feynman-diagrammatic/effective potential method and a resummation of the leading and subleading logarithmic corrections from the scalar-top sector has been published [32] in the latest version of the code **FeynHiggs** [7, 12, 30, 31, 32].

More recently the calculation of the momentum dependent two-loop QCD corrections to M_h have been presented [33]. (From a technical point of view we have calculated the momentum dependent two-loop self-

energy diagrams numerically using the program `SecDec` [34, 35, 36].) Subsequently, in Ref. [37] this calculation was repeated (differences of the two calculations are discussed in Ref. [38]), where also a calculation of the two-loop corrections of $\mathcal{O}(\alpha\alpha_s)$ were presented. The results of Ref. [33] are publicly available in the code `FeynHiggs`.

The remaining theoretical uncertainty in the calculation of M_h , from unknown higher-order corrections, had been estimated to be up to 3 GeV, depending on the parameter region. Recent improvements have potentially lead to a somewhat smaller estimate of up to ~ 2 GeV [32, 39] for not too large SUSY mass scales. However, a careful re-analysis of this uncertainty for lower and heavier SUSY mass scales is in order. As the accuracy of the M_h prediction should at least match the one of the experimental result, further sub-dominant higher-order corrections have to be included in the Higgs-boson mass predictions [40].

III. COUPLING STRENGTH ANALYSIS AT THE LHC AND BEYOND

Testing the coupling strengths of the discovered Higgs boson could yield hints towards an extended Higgs sector, where the MSSM Higgs sector makes clear predictions for possible deviations. In order to test the compatibility of the predictions for the SM Higgs boson with the (2012) experimental data, the LHC Higgs Cross Section Working Group proposed several benchmark scenarios for “coupling scale factors” [41, 42] (see Ref. [43] for a recent review on Higgs coupling extractions). Effectively, the predicted SM Higgs cross sections and partial decay widths are dressed with scale factors κ_i (and $\kappa_i = 1$ corresponds to the SM). Several assumptions are made for this κ -framework: there is only one state at 125 GeV responsible for the signal, the coupling structure is the same as for the SM Higgs (i.e. it is a \mathcal{CP} -even scalar), and the zero width approximation is assumed to be valid, allowing for a clear separation and simple handling of production and decay of the Higgs particle. The most relevant coupling strength modifiers are $\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, \kappa_\gamma, \kappa_g, \dots$.

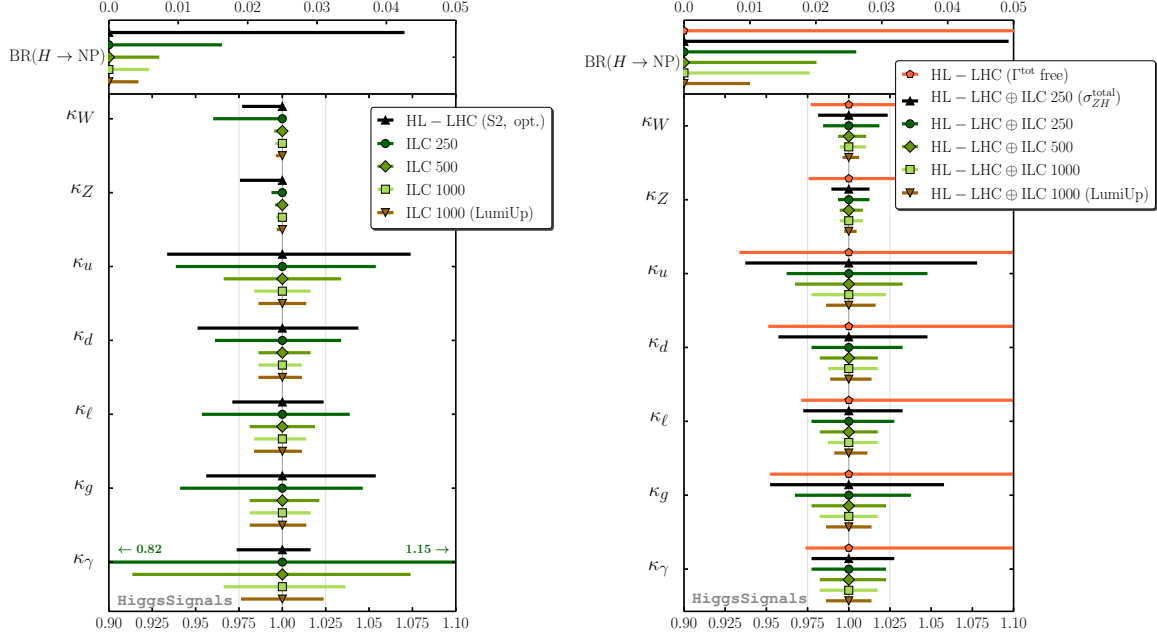
One limitation at the LHC (but not at the ILC) is the fact that the total width cannot be determined experimentally without additional theory assumptions. In the absence of a total width measurement only ratios of κ ’s can be determined from experimental data. An assumption often made is $\kappa_{W,Z} \leq 1$ [44]. A recent analysis from CMS using the Higgs decays to ZZ far off-shell yielded an upper limit on the total width about four times larger than the SM width [45]. However, here the assumption of the equality of on-shell and off-shell couplings of the Higgs boson plays a crucial role. It was pointed out that this equality is violated in particular in the presence of new physics in the Higgs sector [46, 47].

In the left plot of Fig. 1 we compare the results estimated for the HL-LHC (with 3ab^{-1} and an assumed improvement of 50% in the theoretical uncertainties) with the various stages of the ILC under the theory assumption $\kappa_{W,Z} \leq 1$ [48]. This most general fit includes $\kappa_{W,Z}$ for the gauge bosons, $\kappa_{u,d,l}$ for up-type quarks, down-type quarks and charged leptons, respectively, as well as κ_γ and κ_g for the loop-induced couplings of the Higgs to photons and gluons. Also the (possibly invisible) branching ratio of the Higgs boson to new physics ($\text{BR}(H \rightarrow \text{NP})$) is included. One can observe that the HL-LHC and the ILC 250 yield comparable results. However, going to higher ILC energies, yields substantially higher precisions in the fit for the coupling scale factors. In the final stage of the ILC (ILC 1000 LumiUp), precisions at the per-mille level in $\kappa_{W,Z}$ are possible. The 1 – 2% range is reached for all other κ ’s. The branching ratio to new physics can be restricted to the per-mille level.

Using ILC data the theory assumption $\kappa_{W,Z} \leq 1$ can be dropped, since the “ Z -recoil method” (see Ref. [49] and references therein) allows for a model independent determination of the HZZ coupling. The corresponding results are shown in the right plot of Fig. 1, where the HL-LHC results are combined with the various stages of the ILC. The results from the HL-LHC alone continue to very large values of the κ ’s, since the fit cannot be done without theory assumptions. Including the ILC measurements (where the first line corresponds to the inclusion of *only* the $\sigma_{ZH}^{\text{total}}$ measurement at the ILC) yields a converging fit. In the final ILC stage $\kappa_{W,Z}$ are determined to better than one per-cent, whereas the other coupling scale factors are obtained in the 1 – 2% range. The branching ratio to new physics is restricted to be smaller than one per-cent. This opens up the possibility to observe MSSM induced deviations in the Higgs boson couplings, provided that the overall Higgs mass scale, M_A , is not too large.

IV. THE SEARCH FOR ADDITIONAL HIGGS BOSONS

Many investigations have been performed analyzing the agreement of the MSSM with a Higgs boson at ~ 125 GeV. In a first step only the mass information can be used to test the model, while in a second step also the rate information of the various Higgs search channels can be taken into account (see the previous section).

FIG. 1: Fit to the coupling scale factors with (left) and without the theory assumption of $\kappa_{W,Z} \leq 1$ [48].

Here we briefly review some results in two of the new benchmark scenarios [50], devised for the search for heavy MSSM Higgs bosons. In the left plot of Fig. 2 the m_h^{\max} scenario is shown. The red area is excluded by LHC searches for the heavy MSSM Higgs bosons, the blue area is excluded by LEP Higgs searches, and the light shaded red area is excluded by LHC searches for a SM-like Higgs boson. The bounds have been obtained with HiggsBounds [51] (where an extensive list of original references can be found). The green area yields $M_h = 125 \pm 3$ GeV, i.e. the region allowed by the experimental data, taking into account the theoretical uncertainty in the M_h calculation as discussed above. Since the m_h^{\max} scenario maximizes the light \mathcal{CP} -even Higgs boson mass it is possible to extract lower (one parameter) limits on M_A and $\tan\beta$ from the edges of the green band. By choosing the parameters entering via radiative corrections such that those corrections yield a maximum upward shift to M_h , the lower bounds on M_A and $\tan\beta$ that can be obtained are general in the sense that they (approximately) hold for *any* values of the other parameters. To address the (small) residual M_{SUSY} dependence (M_{SUSY} denotes the average scalar top mass scale) of the lower bounds on M_A and $\tan\beta$, limits have been extracted for the three different values $M_{\text{SUSY}} = \{0.5, 1, 2\}$ TeV, see Tab. I [52]. For comparison also the previous limits derived from the LEP Higgs searches [53] are shown, i.e. before the incorporation of the Higgs discovery at the LHC. The bounds on M_A translate directly into lower limits on M_{H^\pm} , which are also given in the table. More recent experimental Higgs exclusion bounds shift these limits to even higher values, see the left plot in Fig. 2. Consequently, the experimental result of $M_h \sim 125 \pm 3$ GeV requires $M_{H^\pm} \gtrsim m_t$ with important consequences for the charged Higgs boson phenomenology.

In the right plot of Fig. 2 we show the $m_h^{\text{mod}+}$ scenario that differs from the m_h^{\max} scenario in the choice of X_t (the off-diagonal entry in the scalar top mass matrix). While in the m_h^{\max} scenario $X_t/M_{\text{SUSY}} = +2$ had been chosen to maximize M_h , in the $m_h^{\text{mod}+}$ scenario $X_t/M_{\text{SUSY}} = +1.5$ is used to yield a “good” M_h value over the nearly the entire M_A - $\tan\beta$ plane, which is visible as the extended green region.

M_{SUSY} (GeV)	Limits without $M_h \sim 125$ GeV			Limits with $M_h \sim 125$ GeV		
	$\tan\beta$	M_A (GeV)	M_{H^\pm} (GeV)	$\tan\beta$	M_A (GeV)	M_{H^\pm} (GeV)
500	2.7	95	123	4.5	140	161
1000	2.2	95	123	3.2	133	155
2000	2.0	95	123	2.9	130	152

TABLE I: Lower limits on the MSSM Higgs sector tree-level parameters M_A (M_{H^\pm}) and $\tan\beta$ obtained with and without the assumed Higgs signal of $M_h \sim 125.5$ GeV. The mass limits have been rounded to 1 GeV [52].

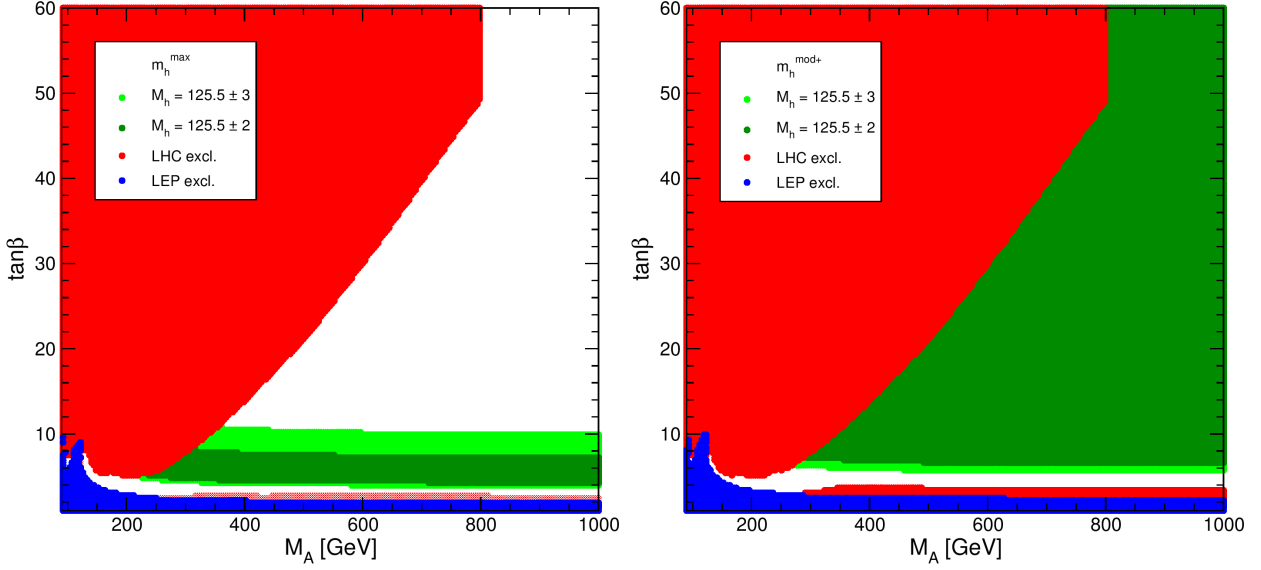


FIG. 2: M_A - $\tan\beta$ plane in the m_h^{\max} scenario (left) and in the $m_h^{\text{mod}+}$ scenario (right) [50]. The green shaded area yields $M_h \sim 125 \pm 3$ GeV, the red area at high $\tan\beta$ is excluded by LHC heavy MSSM Higgs boson searches, the blue area is excluded by LEP Higgs searches, and the red strip at low $\tan\beta$ is excluded by the LHC SM Higgs searches.

V. PRECISION PREDICTIONS FOR THE DECAY OF HIGGS BOSONS TO SUSY PARTICLES

Depending on the scale of Higgs and SUSY masses the main decay channels of the additional Higgs bosons could go to SUSY particles, which is demonstrated in Fig. 3 [50]. The branching ratios for the decay of H and A into charginos and neutralinos may become large at small or moderate values of $\tan\beta$. In Fig. 3 we show the $m_h^{\text{mod}+}$ (left) and $m_h^{\text{mod}-}$ (right) scenarios [50], where the masses of the charginos and neutralinos are $\mathcal{O}(200$ GeV). The excluded regions from the Higgs searches at LEP and the LHC are as before. The color coding for the allowed region of the parameter space indicates the average value of the branching ratios for the decay of H and A into charginos and neutralinos (summed over all contributing final states). One can see from the plots that as a consequence of the relatively low values of the chargino/neutralino masses in these benchmark scenarios the decays of H and A into charginos and neutralinos are kinematically open essentially in the whole allowed parameter space of the scenario, with the exception of a small region with rather small M_A . The branching ratios for the decays of H and A into charginos and neutralinos reach values in excess of 70% for small and moderate values of $\tan\beta$. Including these channels into the searches for heavy MSSM Higgs bosons could potentially allow to discover new Higgs bosons and SUSY particles at the same time.

Recently, full one-loop calculations for the decays of Higgs bosons to scalar fermions [54] and into charginos/neutralinos [55] in the MSSM with complex parameters (cMSSM) have become available. In Fig. 4 we show the results for the decay $h_i \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ ($i = 2, 3$), where details and parameter settings can be found in Ref. [55]. h_2 and h_3 are the two neutral heavy Higgs bosons in the cMSSM, corresponding to H and A in the real case. In the left plot of Fig. 4 the decay widths at the tree- and at the full one-loop level are shown as a function of M_{H^\pm} (at $M_{H^\pm} \sim 1000$ GeV and $M_{H^\pm} \sim 1520$ GeV a mass crossing of h_2 and h_3 takes place, see Ref. [55] for details). It can be seen that the (in this case purely electroweak) one-loop correction can change the decay width by up to 20%. In the right plot of Fig. 4 the decay widths are shown as a function of φ_{M_1} , the phase of the $U(1)$ gaugino soft SUSY-breaking parameter. Changing the phase can lead to effects of up to 50%, while the one-loop corrections again can be as large as 20%. These examples show that complex parameters and the full one-loop corrections should be taken into account for the interpretation of the searches for charginos/neutralinos as well as for any future precision analyses of those decays.

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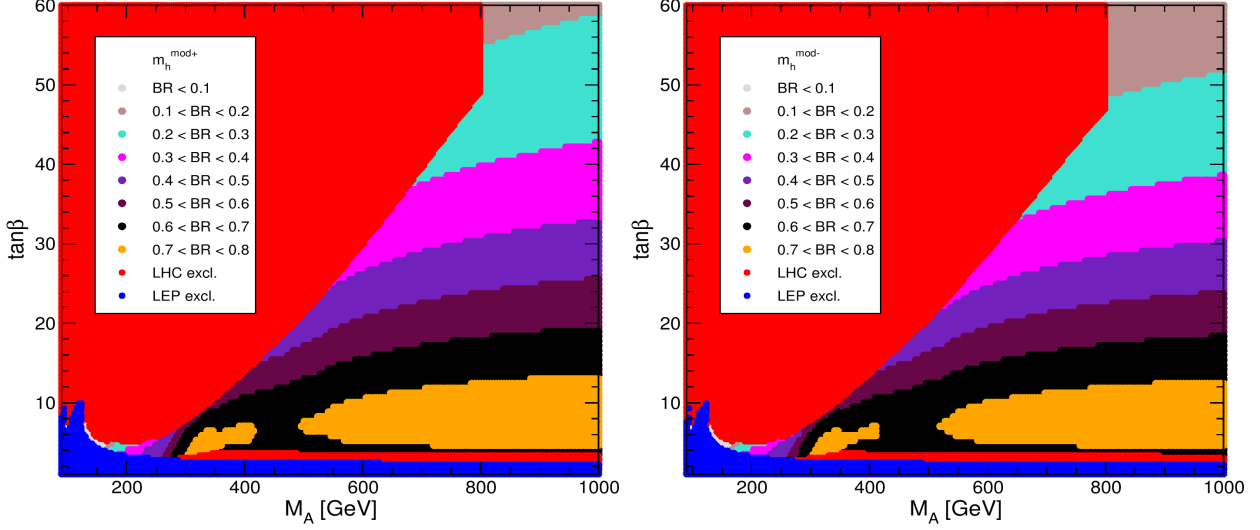


FIG. 3: M_A - $\tan\beta$ plane in the $m_h^{\text{mod}+}$ scenario (left) and the $m_h^{\text{mod}-}$ scenario (right) [50]. The exclusion regions are shown as in Fig. 2, while the color coding in the allowed region indicates the average total branching ratio of H and A into charginos and neutralinos.

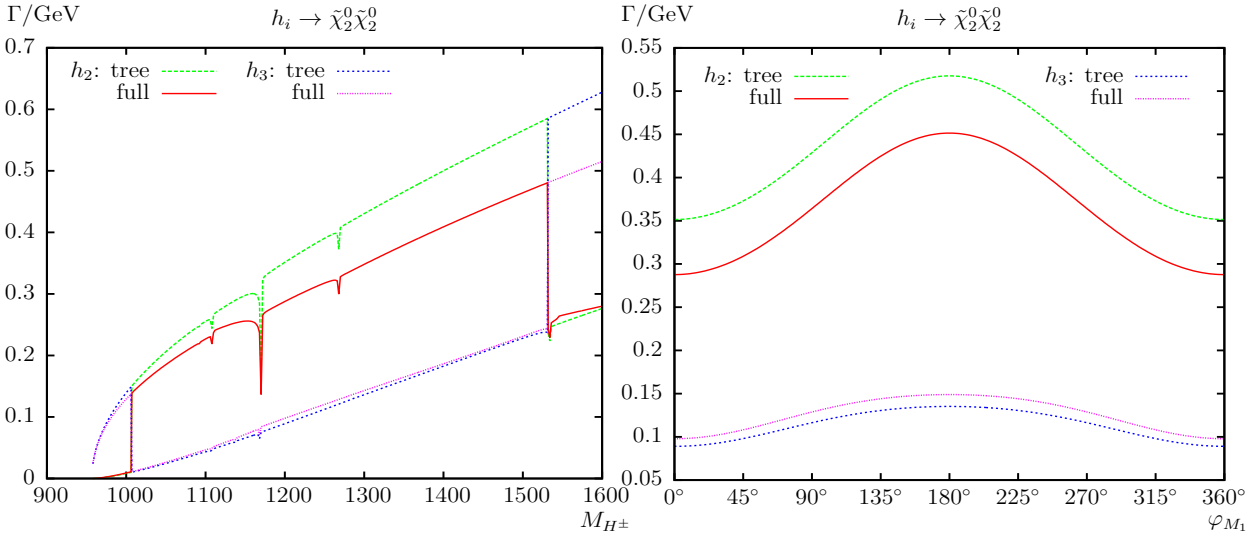


FIG. 4: $\Gamma(h_i \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0)$. Tree-level and full one-loop corrected partial widths for $h_i \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ ($i = 2, 3$) are shown [55]. The left plot shows the partial decay width with M_{H^\pm} varied. The right plot shows the complex phase φ_{M_1} varied (see text).

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